ILLUSIONS OF THE UPPER AIR.[1]

A Review of Progress in Meteorological Theory in England since 1866.

Structure of the Atmosphere according to the Observations of the Upper Air.

But if the ideas which were common in meteorological practice fifty years ago are now to be regarded as illusory, let us consider what we have in their place. We go back to the three elements: the circulation, the convergence, and the convection. As to the circulation, we now think of it as it is exhibited in the upper air, and instead of regarding it as an incidental disturbance of the motion from high to low, we regard it as the foundation of atmospheric structure; as the motion of air which is persistent because the pressure-gradient is balanced by the centrifugal action of the earth's rotation, which we may call the geostrophic component, and of the curvature of the path over the earth's surface, which we call the cyclostrophic component. If the balance between velocity and pressure is not perfect, the difference from perfection can be only infinitesimal, because in the free atmosphere the air must always begin to adjust itself to the strophic balance from the moment that any infinitesimal change becomes operative, and the power of adjustment arising from the extreme mobility of the air prevents any finite perturbation being set up, except temporarily in those regions where violent convection is operative. It is only through the mobile air that perturbation can be transmitted. We no longer picture to ourselves the air as being somehow held firm without moving until a pressure distribution is set up and then let go; the first symptom of pressure-difference will be the occasion of motion, the distribution and velocity grow together; they adjust themselves automatically. The whole history of the general motion of the atmosphere is the story of the constant pursuit of the strophic balance, the adjustment of velocity to pressure, constantly disturbed by infinitesimal changes.

Near the surface things are much more complicated, because there is turbulence due to the interference of the surface and the obstacle which it offers to the steady progress of air. The air loses some of its motion, and is exposed to the pressure without the velocity that is required to balance it. It must, therefere, fall away towards the low pressure, taking out of the pressure the energy necessary to provide for the loss by friction. Thus the convergence which we have to account for is only that shown near the surface within half a kilometre. We need not trouble ourselves about a supposed convergence and convection over the whole area in the upper air. The second element of our specification disappears. After years of contemplation of the motion of the air from high to low as produced in a quiescent atmosphere by the operation of pressure-difference and kept within bounds by friction, we now regard the motion from high to low as actually caused by the friction which retards the velocity required to maintain the strophic balance. To base the theory of motion of the upper air upon the idea of a given distribution of pressure setting a quiescent atmosphere in motion is as great an error as to begin the lunar theory by supposing the moon to start from rest under the force of the earth's attraction, and only to find out after it had started that the earth was moving.

As to convection, there is certainly convection wherever there is instability or the juxtaposition of air of different densities. It takes a great variety of forms; it is very common in cyclones, but it is not a necessary attribute of them. Possibly it is set up there more easily because the air travels so much faster in cyclonic areas than it does in anticyclones, and adjoining localities are fed from different sources of supply. Apart from a certain interference due to change of latitude, the convection is probably the one disturbing cause of the strophic balance of velocity and pressure. So we regard the troposphere as a layer of about 9 kilometres thick, always striving to arrange its motion according to the pressure, and perpetually baffled in its endeavours by the ubiquity of convection. But since all the changes proceed by infinitesimal steps, there is never a time when we can identify a state of finite divergence from the balance between velocity and pressure. From this point of view the centre of a cyclonic or anticyclonic system has no special dynamical importance. It becomes a notable feature on the map when for any reason the cyclostrophic component is the chief element in balancing the pressure. That is seldom the case in our maps, which more often consist of isobars of complicated shapes.

The Dominance of the Stratosphere.

Further than this, Mr. Dines has thrown a new light upon the origin of differences of pressure at the surface by obtaining the correlation coefficient between corresponding deviations of pressure from the normal at the level of 9 kilometres and at the ground, and has obtained results "ranging from 0·67 for the last available set of a hundred soundings on the Continent to 0·88 for soundings in England grouped for the winter season." Moreover, the standard deviations are of the same order of magnitude at both levels—that is to say, both levels are subject to similar changes. At the same time, the correlation coefficient between the pressure at the surface and the mean temperature of the 9-kilometre column is small; in other words, the temperature of the lower strata of the atmosphere has, on the whole, little to do with the general distribution of surface-pressure in this country. Its effects are local.

We must therefore regard the general flow of air, except in so far as it is disturbed by convection, as governed not by what happens at the surface, but by what is imposed upon it from the stratosphere above. It is from there that the general control of the distribution of our pressure comes. It is only modified by what happens below. The upper air, the stratosphere, is the operator, and the lower air the subject operated on. After fifty years of strenuous endeavour to regard the surface as the operator and the upper air as the subject, the exchange of *rôle* is very disturbing, but it has its compensations. There are many things which can easily be explained by operation from above, but only with the greatest difficulty by operation from below. Let us indulge in some speculations which follow from supposing that the stratosphere operates upon the troposphere. It makes the troposphere as tuneful as an organ under the alternating rarefaction and compression caused by the changes in the stratosphere. Every cloud is the subject of its action. One can imagine them being developed, showing first the region of greatest humidity, like the development of a photographic plate, which further develops into loss of stability, and so into cumulus-cloud and a shower. And let us not forget that each several cloud means the disturbance of the normal circulation; the condensation will alter locally the horizontal distribution of temperature, and therefore that of pressure and wind. On the table are two autochrome photographs of the western sky at Ditcham Park, with a quarter of an hour's interval, on a September evening in 1911, with gradually reddening clouds that gradually vanished as they approached from the west. Nothing could be more attractive than to speculate upon such changes in relation to the changes of pressure in the stratosphere

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[1] From a discourse delivered at the Royal Institution on Friday, March 10, by Sir Napier Shaw, F.R.S. Continued from p. 194.

The Régime of the Stratosphere.

But our new point of view only shows our problem removed one step further; we have now to begin again and imagine for ourselves what is the *régime* of pressure and winds in the stratosphere until the enterprise of meteorologists completes our knowledge of what it actually is. The problem is, at any rate, much simplified, because convection is avoided; we deal with an atmosphere which, being nearly isothermal, is inherently stable; density goes directly with pressure, layer lies on layer like a light liquid on a heavy one; temperatures are uniform, or very nearly so, in the vertical direction, and therefore isotherms are also isobars, and winds are proportional everywhere to pressure-differences—that is, to temperature-differences. Outside the equatorial region the rotation of the earth secures that air always moves along the lines of pressure, keeping high pressure or low temperature on the right. So the general idea is simple, but whether the streams of air are long, straight currents or centrical whirls we do not yet know.

Numerical Calculations.

Speculations of a qualitative character are apt to lead the speculator into serious error; the real test of any physical theory is its quantitative application.

It will be of great advantage to the further development of our ideas if we can trust implicitly to the hypothesis of pressure balanced by motion (let us call it the principle of strophic balance) as the foundation of the structure of the atmosphere, and that hypothesis will be confirmed in the orthodox scientific manner if the quantitative conclusions to be drawn from it are verified by observation. I propose to ask your attention to some applications of that hypothesis which can be tested numerically.

From this point of view the theory of strophic balance has the great advantage of giving a definite relation between wind velocity, pressure, and temperature, and therefore brings the relations between all these quantities within the region of arithmetical computation.

Let us consider some of these relations. We require a number of symbols for the meteorological quantities :—

p	represents the atmospheric pressure
θ	,, ,, ,, temperature
ρ	,, ,, ,, density
l	,, ,, horizontal distance
h	,, ,, vertical height
$s\left(=\frac{dp}{dl}\right)$	,, ,, horizontal pressure gradient
$q\left(=\frac{d\theta}{dl}\right)$	,, ,, ,, temperature gradient
v	,, ,, velocity of the wind
$R=p/(\rho\theta)$	,, ,, constant of the gas equation.

Certain geodesic quantities also come in, viz. :—

E, the radius of the earth.

g, the acceleration of gravity.

r, the angular radius of a small circle on the earth's surface which indicates the path of air in a cyclone.

λ, the latitude of the place of observation.

ω, the angular velocity of the earth's rotation.

We require also some convention as to the positive and negative of v.

v positive represents the winds when the pressure-difference Δp represents higher pressure on the right of the path.

The fundamental relation between the velocity of the wind at any level and the pressure-gradient there is :—

$$s=\frac{dp}{dl}=2\omega v\rho\sin\lambda\pm\frac{v^2}{E}\rho\cot r \quad . \quad . \quad (F)$$

The two terms which make up the right-hand side of this equation are of different importance in different places and circumstances; for example, if the air is moving in a great circle r is 90° and cot r is zero; the first term alone remains. On the other hand, at the equator the latitude $\lambda=0$, sin λ is zero, and the second term alone remains. Away from the equatorial region the second term is relatively unimportant unless the velocity v is great. In temperate and polar latitudes the path of the air differs little from a great circle except in rare cases near the centre of deep depressions; consequently the first term may be regarded as the dominant term in these regions.

We call the wind computed according to the first term the geostrophic wind, and regard it as generally representing the actual wind of temperate and polar regions.

We call the wind computed according to the second term the cyclostrophic wind, and regard it as representing the actual wind (in so far as there is any regular or persistent wind at all) in the equatorial regions. It represents the wind of tropical hurricanes, and winds of the same character may also occur locally in temperate regions as tornados and other revolving storms.

Thus we have the following auxiliary equations :—

Horizontal gradient of pressure . . . . . $s=\frac{dp}{dl}$

Horizontal gradient of temperature . . . $q=\frac{d\theta}{dl}$

Winds of temperate and polar regions—geostrophic winds $s=2\omega v\rho\sin\lambda$ . . (1)

Winds of equatorial regions—cyclostrophic winds . . $s=\rho\frac{v^2}{E}\cot r$ . . . (2)

The measurement of pressure $\frac{dp}{dh}=-g\rho$ . . . . (3)

The gaseous laws (assumed for dry air) . . . . $p=R\rho\theta$. . . . . (4)

From these by simple manipulation I have deduced the following :—

For change of pressure gradient with height $\frac{ds}{dh}=g\rho\left(\frac{q}{\theta}-\frac{s}{p}\right)$ . . (A)

For change of wind velocity with height—

geostrophic winds . $\frac{dv}{dh}=\frac{v}{\theta}\frac{d\theta}{dh}+\frac{g}{2\omega\sin\lambda}\frac{q}{\theta}$ (B)

cyclostrophic winds. $\frac{dv^2}{dh}=\frac{v^2d\theta}{\theta dh}+\frac{gE}{\cot r}\cdot\frac{q}{\theta}$ (C)

Deductions from the Theory of Equivalence of Pressure-distribution and Wind.

These equations serve to explain the following facts established by observation[5] :—

1. *Light winds in the central region of an anti-cyclone.*

It follows from the fundamental equation F when the negative sign is taken, as it must be for an anti-cyclone, that the values of v will be given by the roots of a quadratic equation, which will be impossible if v is greater than $\frac{E\omega\sin\lambda}{\cot r}$. This, for a circle of 70 miles' diameter, only allows a velocity of about 4 metres per second.

This is confirmed in practice, and furnishes a crucial test of the two theories. If an anticyclone is a place where air descends and flows outward, its velocity should diminish as the air spreads outwards; but the reverse is the case with an anticyclone.

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[5] The following references may be given for the statements enumerated here :—(1) Barometric Gradient and Wind Force. Report by Ernest Gold. M.O. Publication No. 190. (2) Shaw, Journal of the Scottish Met. Soc., vol. xvi., p. 167, 1913. (3) Shaw, Q. J. Roy. Met. Soc., vol. xl., p. 111, 1914. (4) The Free Atmosphere of the British Isles. Report by W. H. Dines, F.R.S. M.O. Publication, No. 202. C. J. P. Cave, The Structure of the Atmosphere in Clear Weather. (Cambridge University Press.) E. Gold, The International Kite and Balloon Ascents. Geophysical Memoirs, No. 5. M.O. Publication 210*e*. The computations of equations B and C are not yet published; the direction of the wind is regarded as not being subject to change with height. (5) Shaw, Principia Atmospherica. Proc. R.S.E., vol. xxxiv., p. 77, 1914.

2. *The small influence of the troposphere, and therefore the dominance of the stratosphere, in the distribution of surface pressure.*

This follows directly when numerical values are inserted in equation A. The right-hand side of the equation consists of two terms which are of opposite sign and, numerically, approximately equal in the middle regions of the troposphere. Their combined effect for the whole range is therefore relatively small, and the change of pressure produced in the troposphere is unimportant. The distribution of the stratosphere is dominant throughout the troposphere.

3. *The apparently capricious variations of wind and temperature with height disclosed in pilot-balloon ascents and by ballons-sondes.*

The results of the observations of ballons-sondes show local variations of temperature and those of the observations of pilot balloons show similar variations of the direction and velocity of wind. These variations can be connected numerically by Equation A in combination with Equation 1. A number of examples are given in a paper read before the Royal Meteorological Society. To quote one, the rapid transition from a southerly wind at 1100 metres through a calm to a northerly wind at 1500 metres on October 16, 1913, was shown to indicate a temperature gradient of 7° per hundred kilometres towards the east a condition that was in satisfactory accord with the meteorological circumstances of the time.

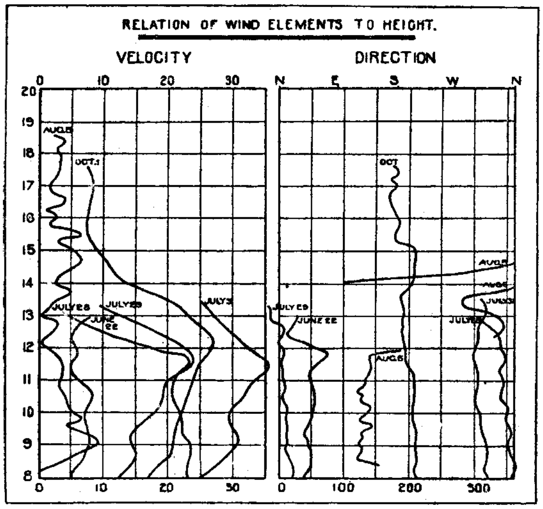

FIG. 1.—Diagrams showing the falling off of wind velocity in the stratosphere (about 11 kilometres). The scale on the left gives the heights in kilometres, those at head and foot the velocity in metres per second, and the direction in degrees from north respectively.

The same combination of equations enables us to specify the *conditions under which "Egnell's law,"* that wind velocity at different heights is inversely proportional to the density at those heights, may be expected to be verified and the conditions prescribed are essentially reasonable.

4. *The rapid falling off of wind in the stratosphere noted in observations with pilot balloons.*

This is illustrated by Fig. 1, a diagram compiled from the figures of high soundings reproduced in Captain Cave's "Structure of the Atmosphere in Clear Weather." The result follows directly from the application of Equation B to the special conditions of the stratosphere. The computations for the four occasions in which there was a wind of considerable magnitude at the base of the stratosphere give the following results:—

Date 1908	Rate of change of velocity in the stratosphere	Horizontal temperature gradient	
		Computed.	Observed.
	m/s per kilometre	Degrees per 100 kilometres	Degrees per 100 kilometre
October 1	− 7	2·1	—
July 31	− 5	1·5	—
July 29	−11	3·3	3·3
July 28	−13	4·0	—
July 27	—	—	2·5

The calculation has been arranged to give the computed horizontal temperature-gradient, because the values of that quantity can be taken directly from the models of temperature distribution constructed in the Meteorological Office for July 27 and 29, Figs. 2 and 3. The order of magnitude which is indicated is quite reasonable, and for the one occasion on which the two can be compared the agreement turns out to be exact. That may be fortuitous; but we may take advantage of the circumstance to use the combination of the figures for the wind in the stratosphere and the horizontal temperature gradient at 13 kilometres to compute the latitude of the place of observation with an accuracy that may lead us to reconsider the common remark that meteorology is not an exact science.

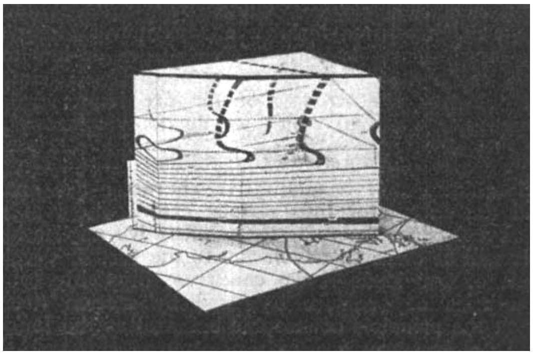

FIG. 2.—Glass model showing the distribution of temperature in the atmosphere on July 27, 1908. Isotherms are drawn for every 5° A., and the thickness of each line represents half a degree except in the case of the isotherm of 273°, which is covered by a band 5° in width. The height of the model represents 24 kilometres. The tilting upward of the isothermal lines shows the commencement of the stratosphere at about 11 kilometres.

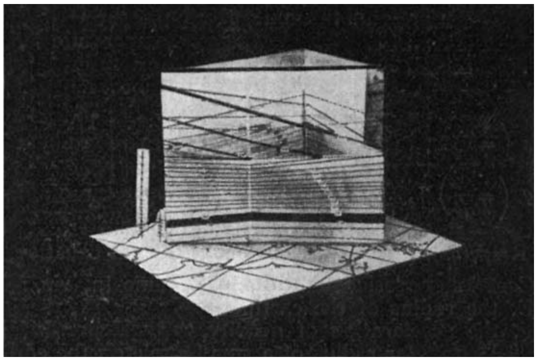

FIG. 3.—Model showing the distribution of temperature in the atmosphere on July 29, 1916. In each case the model stands on a map of the British Isles upon which the isobars are shown. In the interval of two days a layer of cold air spread itself along the base of the stratosphere from the east, and raised the surface pressure by about 10 ml.

The same equation applied to the troposphere, *assuming normal values for temperature, gives cor-*

rectly the rate of change of velocity with height, as shown in the corresponding diagram.

5. *The permanence of vortical motion about a vertical axis in the atmosphere, which is indicated by the long travel of cyclonic depressions.*

From Equation C applied to the stratosphere it follows that a circulation in the base of the stratosphere with a given horizontal temperature gradient, such as is found there, will have only a limited extension upwards. With a wind velocity of 20 metres per second and a horizontal temperature gradient of 5° per hundred kilometres, the extension will be 1·4 kilometres upwards; so that the vortex will be covered by a cap in which the velocity gradually falls off to zero within a very limited height.

For the extension downward the calculation is more complicated, but the computed change of velocity is very small, so that the vortex must be regarded as reaching the ground; and it would appear that a vortex extending throughout the troposphere terminating with a cap in the stratosphere is a possible reality.

Thus the hypothesis of an atmosphere in which the wind velocity is everywhere adjusted to balance the pressure distribution enables us to explain many of the ascertained facts that have been disclosed by the investigation of the upper air, and strongly supports the idea that the pressure distribution at the surface is controlled by the stratosphere and only modified locally by convection.

Against the control of the distribution of pressure by the upper atmosphere may be urged the formation of anticyclones over the relatively cold areas of sea and land, especially the winter-anticyclones of the great continents of the northern hemisphere. For the local effect of surface-cold we have to bring into account the effect of eddy motion, some examples of which are given in the "Meteorological Report of the Voyage of the *Scotia* in 1912" by G. I. Taylor, published by the Board of Trade in 1913

If apology be needed for dealing with fundamental hypotheses like these at a time when the attention of the nation is more especially directed to forecasting and other practical problems of the upper air, it is to be found in the fact that it is of the highest importance that meteorologists who have to advise the men of action upon practical questions should approach the consideration of those questions without the bias which necessarily attaches to an erroneous fundamental principle of long standing. The number of meteorologists who are so engaged is at present small —too small for the various duties that belong to the establishment of a proper understanding with regard to the study of weather. But it is increasing, and it must be increased in various ways if those who entrust their lives and fortunes to the free atmosphere are to enjoy all the advantages to which their experience entitles them.

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

GLASGOW.—The late Lady Kelvin of Largs, widow of Lord Kelvin, Chancellor of the University of Glasgow, and for more than fifty years professor of natural philosophy, has bequeathed to the University a legacy of 5000*l.*, free of duty, to be applied by the Senate for promoting research and teaching of physical science in connection with the natural philosophy chair. One of the last public acts of the late Chancellor was to preside at the opening, in 1907, by their present Majesties (then Prince and Princess of Wales), of the magnificent Institute of Natural Philosophy, in which the work of the department is now conducted under his successor, Prof. A. Gray, F.R.S. A great variety of valuable researches have been carried out in the department since its opening. In recent months "war work" of a highly important character has occupied the professor and his staff. The Kelvin Foundation will handsomely supplement the existing endowments, provided by the Carnegie trustees and others, for instruction and investigation. A scheme for the application of the bequest is under the consideration of the Senate. Lady Kelvin has also bequeathed to the University all the decorations and medals conferred on the late Lord Kelvin. These will be displayed, with similar personal memorials of Glasgow professors and alumni, in the Hunterian Museum. A collection of historic apparatus, used by Lord Kelvin in his researches, is exhibited in the Natural Philosophy Institute.

LONDON.—Among the public lectures to be given at University College during the term just begun the following are of particular scientific interest:—"The School of Chemistry at University College: Turner, Graham, Williamson, Ramsay," Prof. J. Norman Collie (Tuesday, May 9, at 5 p.m.); "The Manufacture of Nitrates from Air by Electric Power," E. Kilburn Scott (Monday, May 15, at 5.30 p.m.); "The Rôle of Chemical Science in Civilisation," Prof. F. G. Donnan (Tuesday, May 16, at 5 p.m.). All these lectures are open to the public without fee. Admission to the lectures by Prof. Collie and Prof. Donnan will be by ticket only. Applications for tickets, which should state the name and address of each person for whom a ticket is required, should be sent to the secretary, University College, Gower Street, W.C. A stamped addressed envelope should be enclosed with each application.

A special course on spectroscopy will be given at University College by Dr. S. Judd Lewis. The course will have reference to the requirements of chemical investigation and of industrial processes. It will occupy twelve half-days, and will begin on Friday, May 5, at 3 p.m.

THE Right Hon. J. F. Cheetham, of Eastwood, Stalybridge, Cheshire, who died on February 25, leaving estate of the value of 554,276*l.*, bequeathed 1000*l.* to the Victoria University of Manchester, and the woodland adjoining Eastwood to his executors to be devoted and set apart as a sanctuary or reserve for the fauna and flora of the district.

THE subject for the Jacksonian prize of the Royal College of Surgeons of England for the present year is "Methods and Results of Transplantation of Bone in the Repair of Defects caused by Injury or Disease," and that for 1917 is "The Causation, Diagnosis, and Treatment of Traumatic Aneurysm, including Arterio-Venous Aneurysm." The dissertation for the 1916 prize must reach the college by Saturday, December 30 next. The triennial prize, consisting of the John Hunter medal in gold, or of the medal in bronze, with an honorarium of 50*l.*, will be awarded in 1918, and the subject for it will be "The Development of the Hip-Joint and the Knee-Joint of Man."

THE conference of the National Union of Teachers was held this year at Buxton. The president, Mr. C. W. Crook, delivered his address on April 26. Speaking of education after the war, he maintained that in the curriculum of elementary schools there will undoubtedly be an increase in the amount of time devoted to the elements of science. Woodwork and its concomitant subjects have done much, he said, to relieve our elementary schools from the danger of becoming too theoretical and literary, but these themselves are not sufficient to meet the call for more scien-